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Growth curves and sustained commissioning modelling of renewable energy: investigating resource constraints for wind energy

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Abstract

Several recent studies have proposed fast transitions to energy systems based on renewable energy technology. Many of them dismiss potential physical constraints and issues with natural resource supply, and do not consider the growth rates of the individual technologies needed or how the energy systems are to be sustained over longer time frames. A case study is presented modelling potential growth rates of the wind energy required to reach installed capacities proposed in other studies, taking into account the expected service life of wind turbines. A sustained commissioning model is proposed as a theoretical foundation for analysing reasonable growth patterns for technologies that can be sustained in the future. The annual installation and related resource requirements to reach proposed wind capacity are quantified and it is concluded that these factors should be considered when assessing the feasibility, and even the sustainability, of fast energy transitions. Even a sustained commissioning scenario would require significant resource flows, for the transition as well as for sustaining the system, indefinitely. Recent studies that claim there are no potential natural resource barriers or other physical constraints to fast transitions to renewable energy appear inadequate in ruling out these concerns.

Key words: Growth curves, natural resources, renewable energy, wind energy, sustainability, energy systems

1. Introduction

The global energy system is dominated by fossil fuels with oil, natural gas and coal making up a total of more than 80 % of the primary energy supply (IEA, 2013a). Fossil fuels are finite resources that cannot be used indefinitely, and the combustion of these fuels cause environmental damage, such as anthropogenic climate change (Höök and Tang, 2013). Replacing the use of fossil fuels with different sources of renewable energy is often considered an important part of a more sustainable development process (Lund, 2007), and a wide range of studies have suggested future energy systems based on different renewable energy technologies. These studies can be quite different in nature, utilising different methodologies and proposing widely different energy systems (Grunwald, 2011). A few recent peer reviewed studies stand out by proposing future energy systems almost completely based on energy from the wind and the sun, claimed to be achievable as soon as the year 2050, or even more rapidly by 2030 (García-Olivares et al., 2012; Jacobson and Delucchi, 2009; Kleijn and van der Voet, 2010).

Substituting the entire current energy system based on fossil fuels with renewable energy technologies involves up-scaling a disparate set of small scale industries, and the timeframe to do this within only a couple of decades, can appear optimistic. The implications of the fast growth of the renewable energy technologies needed to do this are often not adequately addressed in the studies proposing future energy systems based on renewable energy. The question of how these energy systems are then to be sustained over a longer time scale are usually not considered. This study aims to add the perspectives of time and scale to evaluating the feasibility of fast energy transitions by taking account of annual growth rates needed to reach proposed future energy systems as well as investigating how an energy system based on renewable energy technologies could be sustained in the long run. This is mainly done by modelling growth patterns needed to reach the installed capacities of wind energy proposed in other studies, taking account of the life expectancies and need for replacement of technology, using wind energy as an example. The requirement of natural resources for the construction of wind energy is quantified on an annual basis to examine the impact on views of potential material constraints.

The growth of renewable energy technologies needed for an energy transition must inevitably come with the growth of an industry capable of manufacturing and installing that technology, capital to finance these investments, as well as an increased demand for certain natural resources. Renewable energy technologies such as wind and solar energy are more metal intensive than current energy sources and a transition to renewable energy would increase demand for many different metals (Kleijn et al., 2011). Several different critical metals have been identified as potential bottlenecks in the deployment of *"low-carbon energy technologies"* (Moss et al., 2011). It has also been argued that a shift to an energy system based on renewable energy would inevitably be largely driven by fossil fuels, and a fast growth of renewables would actually add new fossil fuel demand to current demand during a transition period (Moriarty and Honnery, 2009).

The concept of "*energy return on investment*" (EROI) appears lower for renewable energy technologies than many conventional fossil fuels we currently rely on for our energy supply (Hall et al., 2013). Concerning solar photovoltaics (PV), it has been suggested that high energy input for the production of crystalline silicon solar cells could be a constraint for the growth of this technology, while current thin film technologies could never reach significant production levels due to the use of scarce materials (Tao et al., 2011). Dale and Benson (2013) even claim that the solar PV industry has not yet paid back any net energy to society, partly due to its high relative growth rates, and concludes that both the timing and magnitude of energy inputs and outputs are important factors in determining an energy balance for the solar industry. Others raise issues with the variable production of electrical energy from wind and solar energy as well as the large amount of capital needed for investment in new energy production as potential constraints on this development (Trainer, 2013, 2012). What is not as commonly discussed is how the actual growth patterns of the different energy technologies affect these potential constraints, or how the energy systems are to be sustained over a longer period of time.

This study investigates how different growth patterns reaching proposed installed capacities of wind energy affects potential constraints connected to annual commissioning capacity and resource requirements. First, the proposed energy futures used for the modelling are presented, and the models as well as the underlying assumptions are described. Then, the resulting growth patterns and the related annual commissioning and resource requirements are quantified. The results, the models used as well as different ways to assess natural resource constraints and other potential constraints for growth of renewable energy technology are discussed. Finally, the main conclusions and potential policy implications of the findings are presented.

2. Methodology

2.1 Installed wind capacity

Jacobson and Delucchi (2009) describe an energy system consisting of 51 % wind energy and 40 % solar energy that is "*technically possible*" to achieve before 2030. This scenario is further elaborated on in Jacobson and Delucchi (2011) and Delucchi and Jacobson (2011), where the time frame is postponed due to difficulties in implementing the necessary policies by 2030, but it is still said to be technically feasible to achieve by 2030. Kleijn and Van der Voet (2010) present a similar scenario, with slightly more wind energy but many times more solar PV, since the total energy demand is assumed to be much larger. García-Olivares et al. (2012) propose an energy mix similar to the Jacobson and Delucchi (2009) scenario, but state that solar PV is unlikely to be able to reach these levels due to constraints induced by scarce materials used for solar PV technology and propose using concentrating solar power (CSP) instead. Table 1 summarizes the main features of these three studies as well as the current situation as of 2012.

The studies described in Table 1 all propose energy systems completely based on renewable energy technology, with wind and solar energy making up almost the entire global energy supply by 2030 or 2050. Although important differences occur between the different studies, some interesting similarities exist. While the solar energy contributions vary greatly both in size and technologies chosen, the assumed contribution from wind is very similar between the studies, with suggested installed capacities ranging from 18 to 24 TW. All three studies discuss potential constraints caused by natural resources and conclude that this factor will likely not constrain the development towards the proposed energy future. The growth patterns needed for the individual technologies is not given much attention, and when growth rates of technologies are mentioned it appears as if exponential growth rates are assumed, or at least deemed feasible.

Since the installed capacity of wind energy is similar between the studies, the growth of wind energy is chosen as a case for this study. Both Jacobson and Delucchi (2009) and García-Olivares et al. (2012) propose energy systems reaching around 19 TW of wind power by 2030, which is used as Case 1. Kleijn and Van der Voet (2010) propose 24 TW of wind by 2050 which is used as Case 2. This provides two different time scales on reaching the proposed amount of installed capacity of wind energy of roughly two and four decades.

Ang and Ng (1992) state that growth curves have been used successfully within energy system analysis to model energy resources, energy demand, fuel substitution and energy technology development. This study attempts to describe potential growth patterns of wind energy using both unbounded exponential growth and bounded logistic growth (Höök et al., 2011). Also, a *"sustainable commissioning model"* is used.

2.2 Model description

2.2.1 Exponential growth

Mathematically, exponential growth or decay means that a quantity changes with a fixed fraction per unit time (Bartlett, 1993). This means that relative growth is constant while the absolute growth will increase with time. Jacobson and Delucchi (2011) claim that Jacobson and Delucchi (2009) demonstrated that it is technically feasible to reach the proposed scenario containing 19 TW of installed capacity wind power by 2030. If wind capacity continued to grow from 2011 to 2030 with the historic growth rate of around 26 %, it would reach about 19 TW, indicating that exponential growth at this rate is an underlying assumption. Kleijn and van der Voet (2010) propose a scenario where wind energy reaches 24 TW of installed capacity by 2050, stating that "*an annual growth rate of 14% would be enough to achieve this*", indicating an exponential growth is assumed here as well. This study investigates the implications of fulfilling these growth patterns by letting wind energy grow exponentially reaching 19 TW by 2030 and 24 TW by 2050. Although not specified in the studies, these capacities are then assumed to be sustained to the year 2100, to be able to investigate the implications of sustaining this capacity.

2.2.2 Logistic growth

Höök et al. (2011) point out that in reality all growing systems must eventually be subjected to some form of limitation, where S-shaped or bell-shaped growth patterns are commonly seen for dynamic systems. Historical growth patterns of energy technologies show that cumulative installed capacities have followed S-shaped growth curves, and the function that proved to be the best fit to these historical growth patterns is the logistic curve (Wilson et al., 2013). Equation 1 describes a logistic growth curve

$$P(t) = \frac{A}{1+e^{-k(t-t_0)}} \qquad (1)$$

where $P(t)$ is the installed capacity at time t, A is the asymptote or saturation level, which in this case would be the suggested future installed capacity, k is the diffusion rate or the steepness of the growth curve and t_0 is the inflection point where the maximal growth rate occurs. In the modelling, a logistic curve is fitted to historical installed capacities using the least squares method with A limited to the maximum installed capacity of wind and k and t_0 are variables.

2.2.3 Sustained commissioning model

Laxson et al. (2006) describes a *sustained manufacturing model,* where installed capacity of wind energy grows to reach 10 %, 20 % and 30 % of U.S. electricity demand by 2020 or 2030. After 25 years the capacity installed 25 years earlier are replaced (repowered). The need to replace the capacity after the end of the service life of the wind turbines affects the desired manufacturing capacity of the wind industry. If the installed capacity of wind is to be sustained over a longer time frame, an industry capable of replacing the capacity taken out of use must exist. If the growth trajectory is too slow to reach a manufacturing capacity large enough to replace the old turbines in the future, the actual wind capacity in use can in fact see a drop after the initial goal is reached. On the other hand, if the manufacturing capacity is expanded too fast, the demand for new turbines will drop and leave manufacturing capacity idle.

The *sustained commissioning model* in this study builds upon the ideas proposed by Laxson et al. (2006), with some modifications. The use of the word c*ommissioning* instead of manufacturing is proposed to highlight the fact that taking wind capacity into use is not only about physically producing wind turbines, but requires an entire industry of getting the right materials, manufacturing parts, permission to install wind farms, assembling and installing turbines, as well as getting the wind farms connected to an electrical grid capable of transporting the power to consumers. While Laxson et al. (2006) assume different annual growth rates for different scenarios, this model assumes global growth rates similar to those seen historically as described by Kramer and Haigh (2009). On a global scale, it appears that energy resources have grown by around 26 % annually before the replacement rates of old with new stock tend to make the exponential growth in early development become linear (Kramer and Haigh, 2009).

The installed capacity in use, *P(t),* in year *t c*an be described by

$$P(t) = P(t-1) + p(t) - p(t-T) \qquad (2)$$

where the net annual change in installed capacity is given by annually added capacity *p(t)* and annually decommissioned capacity *p(t-T),* with the technology lifetime *T*. The constant annual installation rate *C* needed to sustain the target capacity *A* is then given by the technology lifetime *T* according to

$$C = \frac{A}{T}\,. \qquad (3)$$

Annually added capacity *p(t)* grows exponentially with annual relative growth rate *r* until the time when *p(t)* is equal to or greater than *C*

$$p(t) = P(0)(1+r)^t, \qquad p(t) \leq C \qquad (4)$$

and switches to a linear growth of

$$p(t) = C \qquad (5)$$

for the rest of the growth period as well as for sustaining capacity indefinitely. This model is proposed as a way to describe a growth pattern for wind energy that would create a commissioning capacity that could be sustained over a longer time frame than just the growth period.

2.3. Model parameters

2.3.1 Historical growth rates of energy systems

Several studies have reviewed historical growth rates of energy resources and found similarities in growth patterns that could be useful in estimating likely future developments. Höök et al. (2012) reviewed historical growth rates of energy output from the six energy resources considered as *global energy systems,* defined as energy sources contributing over 100 Mtoe, or supplying about 1 % of global annual primary energy. These include oil, gas, coal, biomass, hydropower and nuclear power. Generic growth behaviour for these six energy systems was found, with growth rates decreasing as the energy output increased. It is stated that none of the fossil fuels have grown at more than 10 % over longer time periods, and not even the "oil boom" showed sustained growth rates of more than around 7 %. The growth rates for nuclear and hydropower show similar behaviour as those seen for fossil fuels, despite fundamental differences in technology, suggesting that similar growth patterns could be expected for other energy technologies as well.

Kramer and Haigh (2009) find similar tendencies and even propose two empirical laws of energy technology deployment that could limit the rate of energy technology growth, claimed to be remarkably consistent for different energy sources. The first law states that new technologies grow exponentially for a few decades with around 26 % growth per annum, until the energy source becomes "*material*" at around 1 % of the world energy supply. The second law states that growth rates change after reaching this materiality and switch to a linear growth profile until the technology settles at its final market share. The threshold of reaching "*materiality*" when delivering around 1 % of the global energy supply suggested by Kramer and Haigh (2009) coincides with what Höök et al. (2012) defines as a global energy system.

Wilson et al. (2013) compare historical growth rates of energy technologies and find consistent relationships between the growth in cumulative installed capacity and how long the growth takes, following S-shaped growth patterns. Fitting different saturating functions as well as non-saturating (exponential and linear) functions it was found that logistic growth curves provide the best fit to historic data of different energy technologies. Wind energy started to grow in Denmark in 1977 and does not have datasets as long as many other energy technologies. Although Wilson et al. (2013) do not find logistic patterns for global data, or for many regions of wind energy, the data for Denmark appear to show logistic behaviour. This could indicate that other regions are in an early stage of logistic growth, since the beginning of a logistic curve is very similar to exponential growth, and will likely level off at a later time as maturity sets in.

Apparently, all energy technologies and resources have historically grown with very high relative growth rates at an early stage, before levelling off and following something similar to S-shaped growth curves. This behaviour appears to be the same for fossil fuels as well as other energy sources. These historical growth rates of energy resources and technologies do not necessarily mean that future energy systems must follow these growth patterns, but it could be considered likely.

2.3.2 Wind turbine service life

It is common to discuss changes in different energy systems in terms of growth in total energy output, but some studies, such as Wilson et al. (2013), analyse installed capacities of different energy technologies. This approach makes it possible to quantify when in time specific technical installations are made, which in turn can be connected to a need for industrial capacity and specific flows of materials. It is also possible to include an estimated service life for the technology that defines when it will be taken out of use and will need to be replaced.

Technology can be taken out of use for several different reasons, making the assumption of expected service life somewhat difficult to estimate. However, it must be considered certain that they will not last forever. In the case of wind turbines, the end-of-life can be reached due to technical failure or fatigue, or when the turbine no longer satisfies the need or expectations of the user, when a wind farm is either decommissioned or repowered, where the individual turbines are replaced with new ones (Ortegon et al., 2013). The assumed service life will have a significant impact on annual installations needed in the models in this study.

The question then is what a reasonable estimate of service life for a wind turbine is. Ortegon et al. (2013) state that the designed life expectancy for a wind turbine is 20-30 years, but assumes a service life of 20 years. Laxson et al. (2006) state that the design service life of a wind farm is 20 to 30 years but use a 25 year service life in the models. Within the life cycle assessment (LCA) community it appears to be somewhat of a standard to assume a 20 year service life. Kubiszewski et al. (2010) presents a meta-analysis of 119 different turbines from 50 different analyses between 1977 and 2006, where a vast majority assumed a 20-year life span. Davidsson et al. (2012) looked at ten more recent LCAs of wind turbines and found similar tendencies. Dolan and Heath (2012) reviewed and harmonized 72 LCAs on wind turbines and concluded that 20 years was the most commonly cited lifetime estimate as well as a common design life for modern wind turbines. Basically, a 20 year service life appears to be the most reasonable assumption based on current literature.

One of the first countries to build large quantities of wind energy was Denmark, and data on both commissioned and decommissioned facilities exist all the way back to 1977 (Energistyrelsen, 2014). Using the assumption that the wind turbines will be in use for 20 years it is then possible to compare how much capacity that should be decommissioned 20 years after its construction with the actual numbers on decommissioning. Figure 1 shows these theoretical numbers on decommissioning as well as actual historical decommissioned capacity. Although they do not correlate exactly, especially since a large amount of turbines was taken out of use in the year 2002, they appear to follow a similar pattern, and the total cumulative decommissioned capacity of 431 MW comes remarkably close to the theoretical number of 468 MW.

Including an assumption on service life for a technology can have large impacts on the annual installation need for the growth period, but also for the energy system in a longer time frame. Looking at a scenario for 2050, assuming a 20 year service live of wind turbines, only turbines built after 2030 will even be in use at that time. Turbines built between now and 2030 will only be in service during the transition and for scaling up the industry. After 2050 the old turbines will need to be replaced, so an industry capable of sustaining this level of production needs to be in place.

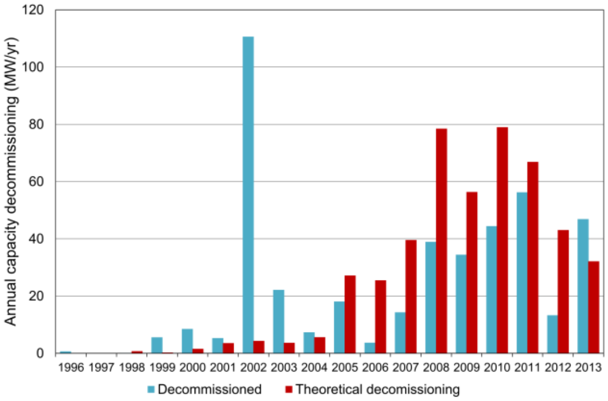

Figure 1. *Historically decommissioned wind capacity in Denmark as well as capacity that should theoretically have been decommissioned when taking account for an estimated service life of 20 years. Data from* Energistyrelsen (2014).

2.3.3 Natural resources used for wind turbine concepts

Although the wind itself is a type of renewable energy, the wind turbines converting the kinetic energy in the wind into electrical energy are not renewable and are built using a wide range of non-renewable resources. There are different wind turbine concepts, which are described in more detail by Polinder et al. (2007). Wind turbines can roughly be divided into two categories: geared turbines and gearless turbines. The turbines can operate with either a fixed speed or limited variable speed concept, both cases using a three-stage gearbox. Turbines operating with variable speed can use either a gearbox or a direct drive train concept. Some concepts use significant amounts of scarce materials in their design. For instance, permanent magnet synchronous generators (PMSG), which is a widely used generator concept with a direct drive train, uses significant amounts of rare earth elements (REEs). These generators often operate without gears, which can be beneficial since the gearbox often needs maintenance. There are other direct drive concepts that do not use these materials, such as induction generators and exited synchronous generators (EESG). The need for rare earth elements is estimated to be 160-200 kg/MW for generators used in direct drive concepts, while PMSG designs used in combination with a gearbox the need for REE is reduced to about 30 kg/MW (Buchert, 2011).

Currently it is mostly off-shore wind technology that relies on rare earth elements and unless new technical concepts are brought to market, the availability of REEs may constrain future plans for the exploitation of the vast wind potential in offshore locations. As a constraint for a total expansion of wind energy on a global scale the significance of these materials are often dismissed since designs not relying on them would likely arise if the supply of these materials becomes increasingly limited. No guess on which designs will be dominant in the future is made in this study, and these materials are not studied in detail. However, wind turbines require large amounts of other materials, such as steel and copper as well, and these materials are quantified in the case study as an example of resource requirements. This study uses the assumption that 1 MW of wind capacity requires 140 tons of iron and steel and 2 tons of copper, as described by Kleijn and Van der Voet (2010).

3. Results

3.1 Growth rates and annual commissioning requirements

The models in the case study provide different views of the annual wind capacity additions needed to reach the proposed energy systems. Table 2 summarises the maximum annual commissioning requirements of the different growth patterns. This annual commissioning of wind capacity means that an industry capable of installing this amount of wind capacity must be in place.

Figure 2a presents the cumulative growth curves of wind capacity enabling 19 TW by 2030 and 24 TW by 2050 with exponential growth profiles. Figure 2b shows the resulting annual commissioning required to reach 19 TW wind capacity by 2030, as well as what is required to sustain this capacity in the future. It can be seen that not only the cumulative installations, but also the annual installations grow exponentially, leading to quite extreme annual installations at the end of the growth period. Reaching 19 TW by 2030 with exponential growth means that 21 % of all installed capacity would be installed in the final year, and 68 % would be installed in the last 5 years. Reaching 24 TW by 2050 with exponential growth means that 11 % of all the capacity would be installed in the final year, and 45 % would be installed in the last 5 years (Figure 2c). Sustaining these capacities will require an annual commissioning growing exponentially in a kind of cyclic behaviour. Similar results were found by Honnery and Moriarty (2011) who used three different exponential growth rates reaching two different installed capacities of wind power and found that these growth rates leads to “boom and bust cycles” in equipment manufacture as well as net energy output from the system. Assuming double digit exponential growth of energy technologies for decades after reaching significant contributions to the global energy system can simply not be considered realistic since the pure arithmetic of such growth patterns leads to unreasonable expectations on annual installation rates. Further discussions on the nature of exponential growth can be found in other studies (Bartlett, 1993; Meadows et al., 1972).

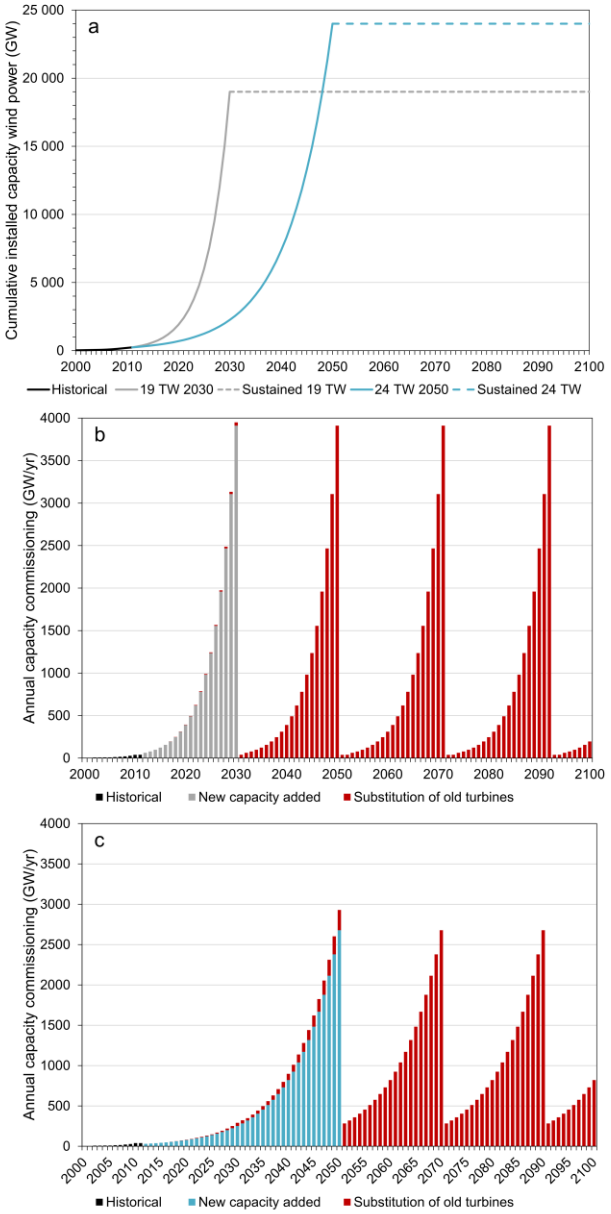

Figure 2. *a) Cumulative installed capacity of wind power reaching 19 TW by 2030 and 24 TW by 2050 with exponential growth. b) Annual commissioning of wind capacity required for reaching 19 TW by 2030 and sustaining this capacity. c) Annual commissioning of wind capacity required for reaching 24 TW by 2050 and sustaining this capacity.*

The exponential growth rate could also be the initial stage of a logistic curve, since this phase of logistic growth is very similar to exponential growth. However, this would require a much higher assumed final installed capacity. Also, the first case reaching 19 TW of wind energy by 2030 is not possible to model with a logistic curve with *A* constrained at this level. Therefore, the remaining case reaching 24 TW by 2050 alone is modelled using a logistic function. Figure 3a describes a logistic growth curve fitted to the historic data and constrained at 24 TW wind capacity. This appears to be a more realistic growth pattern than exponential growth, but what is not always considered is that the annual additions needed will not only be installing new turbines, but also replacing old turbines at the end of their service life. Assuming a 20 year service life for a wind turbine, the annual requirements of replacing old turbines can be modelled with a second logistic curve with a 20 year time lag. Figure 3b shows the annual commissioned capacity needed both for the net growth as well as replacing old capacity taken out of use.

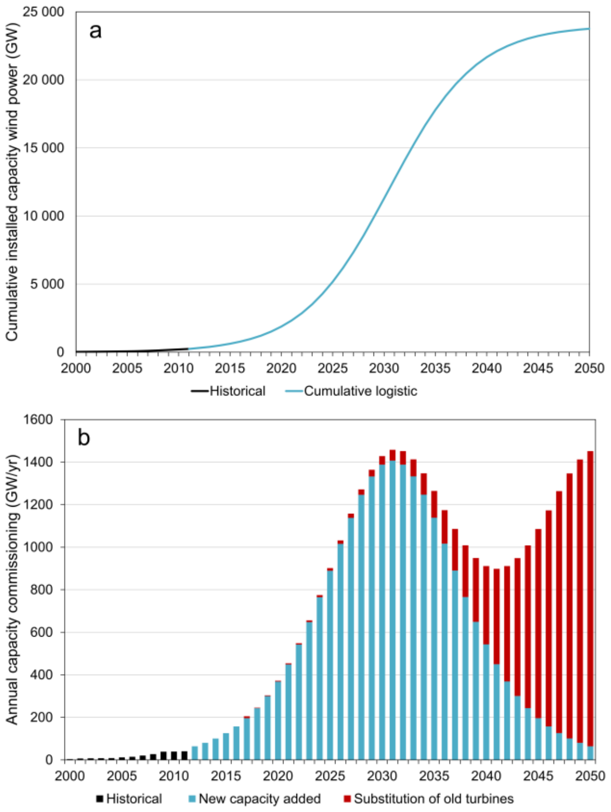

Figure 3. *a) Cumulative installed capacity of wind energy described by a logistic curve fitted to historical data reaching 24TW by 2050. b) Annually commissioned wind capacity required to reach 24TW by 2050 taking account for replacing decommissioned turbines.*

The maximum annual installations needed for logistic growth is much lower than the exponential case, but reaching 24 TW still requires significant numbers. Also, as can be seen in Figure 3b, assuming logistic growth of cumulative installed capacity in this case means that the total annual installations needed when taking account for replacing old turbines creates a dip in annual installation need before rising again. This type of pulsing behaviour is commonly seen in nature (Odum, 2007), and might not be an unrealistic scenario. However, it might not be optimal, since this would create an industry capable of installing more wind capacity in a year than is needed to sustain this in the long run.

By using the *sustained commissioning model* the fluctuations in annual capacity additions can be minimized. Assuming a service life of a wind turbine of 20 years, which appears to be the most common assumption in the literature, sustaining the 24 TW of installed capacity would mean that eventually 1/20 of the installed capacity would need to be replaced every year. A global industry capable of installing more than 1.2 TW could then be considered oversized, and perhaps even unsustainable. In our case study the target capacity A is set to 24 TW and assumed technology life time T to 20 years (see Equation 3). This gives our constant growth rate C at 1200 GW/year. The exponential growth rate r is set to 0.26, to correspond with the historically observed growth rates for energy resources of 26 % (Equation 4).

Figure 4a shows the resulting installed capacity $P(t)$ using the sustained commissioning model, and Figure 4b depicts the annual commissioning requirements of new capacity as well as the replacement of decommissioned turbines. The resulting S-shaped curve reaches the target capacity of 24 TW before year 2050 while still following historically observed growth rates and while minimizing fluctuations in annually added capacity $p(t)$.

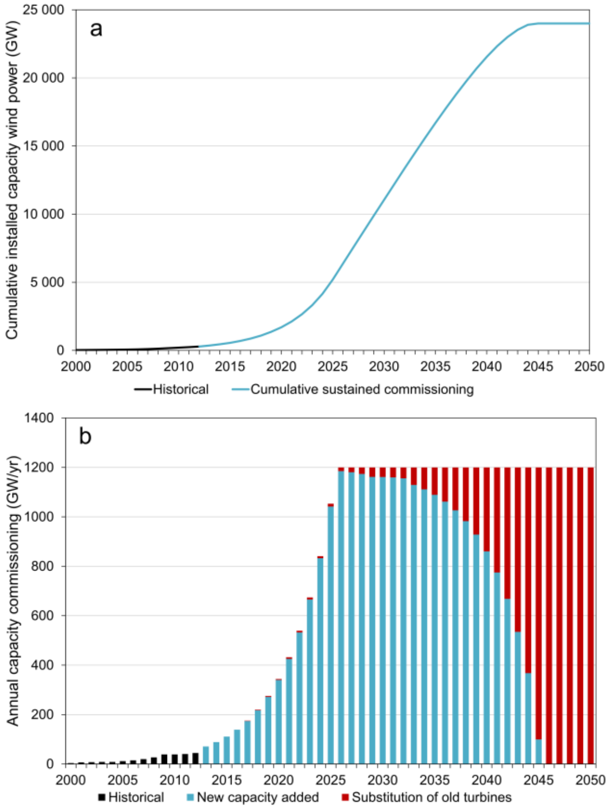

Figure 4. *a) A sustained commissioning growth pattern reaching 24 TW of installed capacity wind energy by 2050, where cumulative installed capacity grows exponentially with 26 % annually until reaching an annual installation rate needed to sustain this installed capacity. b) The associated annual commissioning of wind energy required to reach the same level of capacity.*

3.2 Natural resource requirements

The annual commissioning rates can also be coupled with a requirement for different natural resources and materials. As discussed earlier in this study, many designs use some scarce materials such as REEs. However, as pointed out by Kleijn and Van der Voet (2010), many types of turbines do not depend on these technologies. It is therefore seen as unlikely that REEs would be an unavoidable constraint for the development of wind energy, but more likely limiting for certain wind turbine models using large amounts of these materials. Assuming what fraction of the turbines built in the future will rely on these materials is simply too difficult to predict, and the requirements of these resources are not quantified in this study.

Less scarce materials are commonly ruled out as constraints based on quite simple arguments, but for a complete transition to a renewable energy system even common materials have been mentioned as potentially problematic. Kleijn and van der Voet (2010) suggest that the sheer size of the proposed transition would challenge production even for "*bulk materials*" such as steel and copper. Although the amounts of these materials that are needed can also vary for different designs, it appears inevitable that large quantities will be needed for building wind turbines in the future.

Kleijn and Van der Voet (2010) assumes that 1 MW of wind capacity requires 140 tons of iron and steel and 2 tons of copper, and these assumptions are used in this study for easy comparison. Constructing the wind capacity of 24 TW would only demand a few per cent of global iron ore and copper reserves. However, using the growth patterns from the case study, this total resource requirement can be spread out over the time period leading up to the proposed realisation year and be translated into annual requirements for the different resources. These annual quantities can then be compared with projections for future production of these resources. It could also be useful to take account for competing demand from other uses for a more complete systems view. The quantities presented in Table 2 could give an indication of the size of the annual resource requirements for building these quantities of wind capacity.

Table 2 describes the resulting maximum annual installations derived from the growth patterns modelled in this study. These annual growth rates in production are connected to the annual requirements of steel and copper that this would induce. For an indication of the scale of the resource flows, these quantities are compared to the total global production of these materials in 2012. The exponential growth patterns have been deemed unrealistic, but what is more interesting is that even the apparently more realistic growth patterns lead to significant annual resource requirements. Even in the sustained commissioning model, the annual installation of 1.2 TW needed to sustain the 24 TW wind capacity leads to significant annual requirements for copper and steel. Under these assumptions, only sustaining the 24 TW of wind energy, assumed to provide 15 % of global energy demand by Kleijn and Van der Voet (2010), would need the equivalent of 11 % of total global steel production and 14 % of global copper production (based on 2012 rates of production). This means that reaching and sustaining this installed wind capacity would require quantities of steel that is similar to the current automotive industry, that used 12 % of the steel produced in 2011, while the entire sector of electrical equipment used only around 3 % (World Steel Association, 2012). The amount of copper needed for the turbines is comparable to what is used for making electric motors, of around 12 % of the global copper production, while the electric energy transmission sector use about 26 % (Achzet et al., 2011).

4. Discussion

4.1 Growth curves and the sustained commissioning model

Several recent studies propose future energy systems almost completely based on wind and solar energy, with a stated potential development time frame of two to four decades. The suggested energy systems imply large installed capacities of these technologies, without paying much attention to feasible growth patterns of the technologies or how these installed capacities could be sustained over a longer period in a "*sustainable*" energy system. This study makes no attempt to project what the future energy systems might look like, neither on the demand nor the supply side. Instead, the assumptions of future installed capacity of wind energy for the case study is taken directly from these other studies, and translated into possible growth patterns. It should be mentioned that the works used in this case study are quite extreme when it comes to proposed installed capacities of wind and solar energy compared to most other studies proposing similar energy transitions. However, they are still considered relevant since they are widely cited in peer reviewed scientific journal articles.

The main idea of the growth curves is to translate the proposed wind capacities to annual installation rates, highlighting the perspectives of time and scale for realizing these visions. The fact that the target technologies have limited expected service life adds another dimension to this analysis. The results from the case study should not be interpreted as likely scenarios or predictions for the future, but simply aims to visualise the importance of a dynamic view of fast energy transitions.

Realising the example in the case study, even with the more feasible growth patterns, would imply significant annual requirements for material resources. During the growth phase this demand would be additional to current demand and must be assumed to come from supplementary production, and even if the replacement of turbines in the future would be based on recycling old turbines, a similar sized commissioning industry would be needed, as well as an industry capable of recycling the materials and making them available for new turbines. The pure scale of creating and sustaining this type of energy system is simply massive.

Both from existing literature and from historical data for Denmark, assuming a 20-year service life for wind turbines appears to be the only reasonable assumption. However, it is impossible to know with any certainty how long the turbines will actually be in use, and even if the average service life would be known; they would most likely not all be decommissioned exactly at that point. The models in this study assume that every turbine is taken out of use after exactly 20 years, which is a very theoretical simplification. Also, what will happen to the technology after the end of the service life is largely uncertain and will depend on many different drivers, such as economic and political factors.

4.2 Assessing natural resource constraints

Although many different factors could be the limiting constraint for the growth of renewable energy technology, natural resource requirements and other physical constraints are given the most attention in this study. A different way of looking at potential natural resource constraints than is common in current studies is proposed here. In the studies described in Table 1, investigating potential natural resource constraints appear to be among the main goals. In the case of wind energy, metals considered somewhat scarce, such as neodymium, are sometimes mentioned as a potential issue, but "*bulk*" materials such as steel and copper are usually dismissed as potential constraints. However, none of them pay much attention to assumed growth rates or what resource flows that would be needed to sustain the growth or to sustain the proposed energy system in the future.

Three common ways to evaluate natural resource constraints in other studies have been found. First, the "*Reserve-to-production ratio*" (R/P ratio), comparing the current annual production to reserve estimates is a very common method. Secondly, simply comparing the total demand incurred by the proposed energy system to reserve estimates is a frequently used method. Thirdly, simply stating that the materials used are theoretically recyclable is sometimes used as an argument that no natural resource constraints will occur. All three of these arguments have their merits and can be used to make fast and easy estimates of natural resource constraints, but using any of them to completely dismiss potential problems with natural resource supply appears questionable.

An example of R/P ratio being used to disregard natural resource constraints can be found in Jacobson and Delucchi (2011), where it is stated that the world have "*somewhat limited reserves*" of iron ore, which is claimed to last for 100-200 years at current production. However, this assumes that annual production remains constant and global steel production is currently increasing rapidly, and realizing the Jacobson and Delucchi (2009) scenario would mean a significant increase of an already expanding demand for steel. Comparing current production to reserve estimates could give a first indication of potential constraints, but it appears insufficient to motivate a total dismissal of problems that might occur. Bartlett (2006) describes several problems with using the R/P ratio for a resource under growing production, and states that it gives rise to unwarranted optimism.

The method of comparing the total requirements of a resource for reaching a future energy system to estimated reserves can be found in García-Olivares et al. (2012), where it is stated that the complete power system needed for the energy system described would need 40 % of total estimated copper reserves. Adding assumptions of the copper needed from the demand side of the transport sector García-Olivares et al. (2012) reach a total of 60 % of global copper reserves. This method has the potential of indicating if the quantities needed could be a problem. For instance, the claim that realizing the energy system proposed in García-Olivares et al. (2012) could demand 60 % of the current copper reserves appear like extraordinary quantities, although reserve estimates can change with time. However, this method does not say anything about what resource flows would be needed and how fast the materials could be brought to market.

The third common argument to dismiss potential resource constraints is using the simple fact that some materials are recyclable. Jacobson and Delucchi (2011) argue that some rare resources, such as neodymium for electric motors and generators, platinum for fuel cells and lithium will have to be recycled or replaced with less scarce materials to reach a 100 % renewable energy system, unless additional resources are located. Jacobson and Delucchi (2009) claim that there are indications that there are not enough economically recoverable lithium to build "*anyway near the number of batteries needed in a global electric-vehicle economy*", but at the same time state that recycling could change this equation. There is no doubt that recycling would be important for sustaining a "*sustainable*" energy system in the future, but this does not mean that recycling will change the total amount of materials needed in the system at a given moment in time. The same atoms simply cannot both be in use and recycled to build other technology at the same time. The minimum amount of a resource needed to sustain the system simply does not change because of recycling. A more comprehensive discussion on recycling using the case of lithium is available in Vikström et al. (2013).

The end of life recycling rate (EOL-RR) appears to be around 70-90 % for iron and steel, but since the steel demand is growing and is commonly used for long lived uses, the recycled content (RC) in new material is lower at around 32-52 %, while the same factors for copper has been estimated to be between 43-53 % and 22-37 % respectively (Graedel et al., 2011). While some expect that the recycling rates for metals used in electricity generation technologies will be higher due to expected high collection rates (Elshkaki and Graedel, 2013), others mentions different situations that could lead to materials not being recycled (Davidsson et al., 2012).

For some materials, recycling can even be technically problematic. In the case of REEs, such as neodymium, recycling is commonly mentioned as being important for a sustainable energy system, but at the moment no infrastructure for recycling of REEs from the permanent magnets exists and the end-of-life recycling rate is estimated to be less than 1% (Buchert, 2011). One important problem with recycling rare earth elements is the fact that the metals oxidize quickly and disappear in the slag (Buchert et al., 2009). However, it could be technically possible to reach recycling rates of more than 90% for both neodymium and dysprosium (Schüler et al., 2011).

A sustainable energy system would have to recycle as much as possible of the materials after the end of the service life, but even if recycling rates would eventually come close to 100 %, the industry for replacing old technologies would still demand large resource flows indefinitely. The case study culminating in 24 TW of installed wind capacity demands an equivalent of over 10 % of current (2012) global annual demand of bulk materials such as copper and steel. Even if these turbines were to be recycled at the end of their life and built using only recycled materials, it would still mean large material flows.

Another important perspective is the fact that this study only includes the material demands for constructing wind energy, assumed to supply far from the total global energy demand. An energy system completely based on renewable energy technology would likely need more of these technologies, but also energy storage and transmission capable of creating a functioning energy system. For instance, Barnhart and Benson (2013) investigates energy and material requirements for different energy storage technologies and concludes that building an energy storage capacity that could be required in the future require amounts of materials and energy that are comparable to current annual production values.

Although it appears somewhat uncertain how much, it is evident that energy resources is also used to construct technologies like wind turbines (Davidsson et al., 2012). As pointed out by Dale and Benson (2013), this can potentially limit the growth, since an industry growing too fast can mean that the industry consumes more energy than it produces on an annual basis. Honnery and Moriarty (2011) point out that most of this energy is used before any energy are produced, and the timing of the installations have an impact on the apparent net energy output from the system.

4.3 Other potential constraints for renewable energy

The pure scale of constructing this amount of wind energy can lead to different types of constraints on the growth of wind technology. Natural resources demand has been discussed in more detail in this study, but there are many other examples of potential constraints on the growth of renewable energy technology, many of which are discussed by others. IEA (2013b) mentions costs, grid integration issues and permit issues as obstacles to a goal of 18 % of global electricity from wind energy by 2050. For reaching the energy futures discussed in this study, with many times greater installed capacity of wind than this by 2050, these constraints would naturally be even larger.

Although it is problematic to generalize costs over an entire technology and it appears uncertain what the actual costs for renewable energy technology are and will be in the future (Larsson et al., 2014), building these amounts of energy technology naturally comes with large financial costs. For some energy technologies the cost of fuels and operation and maintenance constitute large parts of the total costs, but for wind energy, constructing the wind turbine and the connected capital costs constitute the majority of the total cost, with 76 – 85 % of the total cost being capital cost (Timilsina et al., 2013). Financing for this cost needs to be in place before the wind capacity can be commissioned. Jacobson and Delucchi (2009) state that the construction of the proposed energy system would cost around 100 trillion USD over 20 years (not including transmission), which will be paid back by the sale of electricity and energy. Trainer (2012) interprets this as an investment of 5 trillion USD annually would be needed, which is said to be around 11 times the early 2000s annual investments in energy of around 450 billion USD. However, as discussed in this paper, this type of growth pattern is not very realistic. The exponential growth rates described in Figure 1 would lead to a more gradual increase in annual investment needs, but would end up in quite absurd sums at the end of the growth period, due to the nature of exponential growth. The growth patterns suggested in this study should not only be considered when assessing natural resource demand, but can very well be considered regarding financing as well.

The variability of production and grid integration is commonly suggested as the main barriers for implementation of renewable energy and it has even been suggested that this factor limits penetration rates of wind energy to 20 % of electricity production (Lenzen, 2010). These factors are discussed in more detail in other studies (Trainer, 2013, 2012). Barnhart and Benson (2013) suggests that an energy storage capacity capable of storing between four and twelve hours of average global power demand could be required in the future, which would require large amounts of materials and energy. The fact that energy production from renewable energy technologies is intermittent and non-dispatchable can also be argued to add to the total costs due to the need for backup power (Larsson et al., 2014). The grid improvements and backup power requirements have to be in place before the variable energy production is taken into use, so the estimated growth curves can prove important for these aspects as well.

5. Conclusions and policy implications

Wind energy and other renewable energy technologies are commonly proposed as an important part of a transition to a *"sustainable"* global energy system. Although these technologies are likely more sustainable than fossil fuels, they are not without environmental impacts and are built using non-renewable resources. They should therefore not automatically be considered sustainable. A rapid growth in these technologies will even increase demand for a variety of different resources. Suitable growth rates of energy technologies, as well as how an energy system can be sustained over a longer time frame, should be considered when discussing sustainable energy systems for the future. The natural resource requirements for a transition to an energy system based on renewable energy technology should be analysed as a dynamic flow problem and not as a matter of static stocks. This study proposes that a *sustained commissioning model* can be used as a theoretical base for these considerations.

In a *sustained commissioning* scenario, an energy technology grows exponentially at levels seen historically for other energy sources, until reaching the level needed to sustain the desired installed capacity over an extended period. The installed capacity continues to grow at this rate, before the limited service life of the technology forces the installed capacity to settle at a level that can be sustained by an annual commissioning of the same capacity. In theory, this can then be sustained indefinitely.

These annual installation levels can also be integrated with estimates for annual resource requirements. Even in the sustained commissioning scenario the required resource flows are significant. Sustaining these flows indefinitely, or at least in the long term, has implications for resource management. Future production of the required resources can similarly be dynamically modelled as annual flows, giving a more useful perspective on possible outcomes. To reach something resembling a sustainable energy system, resources should be recycled when the technology reaches the end of its service life, and is why policies increasing recyclability of renewable energy technologies are crucial.

Policy makers should be aware of the long time frames that will be likely in attaining a global energy system based on renewable energy technology, as well as the potential barriers to these transitions. Some obstacles are socioeconomic, while others relate to the supply of natural resources. Recent assessments claiming there are no potential problems with natural resource supply or other physical constraints to fast transitions to renewable energy appear inadequate in ruling out these concerns. A more holistic view on resources and sustainability is encouraged when planning future energy systems.

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